HOLOCENE CLIMATE, VEGETATION, AND FIRE LINKAGES IN THE UINTA MOUNTAINS, UTAH

by

Lovina Abbott Turney

A thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Geography

The University of Utah

December 2014

The University of Utah Graduate School

STATEMENT OF THESIS APPROVAL

The thesis of **Lovina Abbott Turney**

has been approved by the following supervisory committee members:

Mitchell J. Power	, Chair	**12/18/2013** Date Approved
Andrea R. Brunelle	, Member	**12/18/2013** Date Approved
Eric C. Carson	, Member	**12/18/2013**
Richard L Ford	, Member	**12/18/2013** Date Approved

and by **Andrea R. Brunelle** , Chair/Dean of

the Department/College/School of **Geography**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

A 14,000-year lake sediment record from Heller Lake-Dry Gulch Meadow on the south slope of the Uinta Mountains provides evidence of large-magnitude disturbance events during the Holocene. The modern lake basin which catastrophically drained in the early 20th century provides a uniquely exposed sedimentary archive to examine lake sediments in situ and analyze sediment samples from the lake bottom. Analysis of this sedimentary record explores the climate, vegetation, and fire history, and their potential implications on land management. Pollen and charcoal evidence suggest a large-scale vegetation and fire regime shift at approximately 6,500 cal yr BP when fire activity increased dramatically and dominant vegetation changed from open spruce parkland to closed canopy pine forest. Average fire return intervals have remained relatively stable during the last ~10,000 years; however, frequency and magnitude have decreased during the last few millennia, suggesting the modern montane forest of the Uinta Mountains developed under an infrequent fire regime. The mid-Holocene maximum in fire frequency, with fires averaging one event every ~140 years, may provide a perspective on future trends of increased fires in middle and high elevation forests as snowpack decreases and summer temperatures continue warming. Increased fire frequency in the past has led to major vegetation changes in the Uinta Mountains, and recent trends in fire

activity, such as the large fires in 2007, suggest understanding fire-climate linkages should be a management priority.

To Tom for supporting and encouraging me through this process even though you didn't always understand why I was doing it. And for Jadiree, just because.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

I would like to thank my advisor, Mitchell Power, for his suggestions and help on this project, and for taking on an unknown grad student. I have learned a lot, and have really enjoyed being part of the Power Paleoecology Lab. Many thanks to Eric Carson and Rick Ford for being part of my committee, helping with the project, being encouraging, and spending a wet week in the field with me digging out the pedestal core. It was a lot of fun. Thank you to Andrea Brunelle for also being part of my committee, for her wonderful instruction, and offering encouragement when I really needed it. Thank you to Laurel Lay and the rest of the Power Paleoecology Lab, without whose help I would have never gotten through all the data processing. Thank you to Ann Kelsey for her amazing enthusiasm about everything botanical and being so excited to share and teach about it, and Yoshi Tracy for being awesome. Thank you to Ashley National Forest for supporting this research, with special thanks to Darlene Koener, Helen Kempenich, and Mike DeVito for their enthusiasm, expertise, help with logistics and fieldwork, and especially for the canvas tent for the first week in the field. It would have been much less pleasant without it. To everyone who provided advice, listened to me practice, and helped in anyway, thank you. And finally, to my family for your love, encouragement, and patience; thank you, you are the best.

CHAPTER 1

INTRODUCTION

Paleoecological studies provide an expanded view of ecology over long time periods, providing a context for the historical development as well as the modern structure and function of ecosystems (Pielou 1991). Understanding how systems operated in the past, and how past systems responded to change, is important for understanding how current ecosystems will respond to future changes (Finklestein 2010). Long-term ecological data can play an important role in addressing many of the current environmental issues such as biodiversity change, and conservation and land management and planning (Froyd & Willis 2008). Paleoecological studies are used to build climatic, vegetative, and fire histories at local to regional scales. The information collected from these long-term environmental reconstructions provide baseline information to ascertain recent and past environmental change, determine if past disturbance events are unprecedented, establish restoration goals, and to help inform land management decisions (Seppa & Bennett 2003; Willis et al. 2010).

A common method of conducting paleoecological studies is through multiproxy analysis. Similar to assembling a jig-saw puzzle, a multiproxy approach to long-term environmental reconstructions uses multiple pieces of evidence to form a more complete picture of ecosystem processes in the past, including the effects of natural disturbances, than would be possible with using only a single proxy. The different lines of evidence allow for multiple working hypotheses to be tested (Chamberlin 1890). Ideally, one will see corroboration between different pieces of evidence; for example, an event detected in the charcoal record will also be detected in the pollen record and the magnetic susceptibility record. Common analytical approaches used to interrogate sedimentary archives include pollen, charcoal, loss-on-ignition, macrofossils, radiocarbon dating, and magnetic susceptibility. Historical documents and dendrochronology can also be used where they are available and overlap with the time frame being studied.

While some studies have evaluated modern ecology and biogeography of the Uinta Mountains (Hayward 1952; Briggs & MacMahon 1983; Shaw & Long 2007), little research has attempted to understand long-term ecological processes, including natural disturbances, operating over thousands of years (Carrara et al. 1985; Koll 2011). A recent feasibility study of the Heller Lake/Dry Gulch meadow (HLDGM) was commissioned by Ashley National Forest in 2004 to determine if further study of the meadow was warranted. Five sediment samples were analyzed for the upper 34 centimeters, spanning the last 10,000 years for diatom, pollen, and macrofloral remains (Varney et al. 2004). Seven radiocarbon dates were also submitted, with the lowest sample returning an age of 9980 ± 100 ^{14}C yr BP (radiocarbon years), indicating a record spanning most of the Holocene (the last 11,700 years) (Carson 2003). The initial analyses from the feasibility study suggested a finer resolution study of the meadow should yield a robust representation of the vegetative and environmental changes during the Holocene (Varney et al. 2004).

Wildfire activity in the western US has been increasing in size, frequency, and severity for the past several decades, possibly linked to earlier snowmelt and generally warming climate (Westerling et al. 2006; NRCS 2011; Marlon et al. 2012). The National Climate Assessment Development (NCAD) report indicates that climate change is increasing the vulnerability of forests to ecosystem change and tree mortality through fire, insect infestation, drought, and disease outbreaks, and projects that western forests in the US will be increasingly affected by large and intense fires that will occur more frequently (Joyce et al. 2013a,b). The National Interagency Fire Center also shows that fire activity has been increasing since the 1990s (NIFC.gov). In comparison to the first half of the century, the last 30 years has seen an increase in temperature and a decrease in precipitation variability in the United States (NOAA NCDC). This increase in fire activity along with changes in temperature and precipitation could result in changes to tree density and species composition which ultimately could convert forests to shrub lands and meadows (Joyce et al. 2013a).

Fire management is an important consideration for Ashley National Forest and having a good understanding of the fire history of the forest. Previous knowledge of fire in Uinta montane ecosystems is based on fire-scarred-tree-ring research used to create a local fire history. This tree-ring-based record for the Uinta Mountains is limited to the last 500-years (Heyerdahl et al. 2011). While longer than most instrumental records, the last five centuries is encompassed by the Little Ice Age (LIA) (Mann et al. 2009), a period of protracted global cooling potentially biasing tree-ring based estimates on fire occurrence in the Uinta Mountains. Streamflow reconstructions from tree-ring records suggest that the Uinta Mountains experienced persistent drought during the LIA (Carson & Munroe 2005), suggesting drier conditions in the last several centuries. Fire scar and cohort plots from Heyerdahl et al. (2011) indicate that large fire events can affect multiple habitats that, under typical conditions, would have different fire ecologies. Low-elevation ponderosa pine would have frequent, low severity fire with low tree mortality while high elevation lodgepole pine, spruce, and fir would have infrequent, high severity fires with high tree mortality (Lotan et al. 1985; Uchytil 1991; Anderson 2003).

An example of a recent large fire in the area is the 2007 Neola North fire. The 2007 Neola North fire began burning June 29th, at the peak of the summer-dry conditions, and burned 17,608 ha, including 12 homes (Associated Press 2007; Martin 2007). Three deaths were attributed to the Neola North Fire that also caused evacuation of about 500 residents. The Neola fire began burning at a low elevation and burned upslope and through multiple vegetation zones (Figure 1). The behavior of the Neola fire may provide an analog for understanding historical fires detected by Heyerdahl et al. (2011).

In this study, the role of fire is evaluated within the context of the long-term vegetation history of a montane ecosystem. The goal of this study is to document the vegetation, climate, and disturbance history of the south-central Uinta Mountains, Utah, providing one of the first paleorecords for this region. To accomplish this, multiple hypotheses were created to identify the role of fire in shaping montane ecosystems. First, I hypothesize vegetation has responded to past climate forcing by moving upslope (warming) or downslope (cooling). HLDGM is located near the boundary of the upper montane/alpine ecotone, and should be sensitive to ecotonal boundary shifts as climate changes during the Holocene. The first hypothesis is evaluated by documenting how vegetation has changed during past climate transitions such as the Younger Dryas (YD),

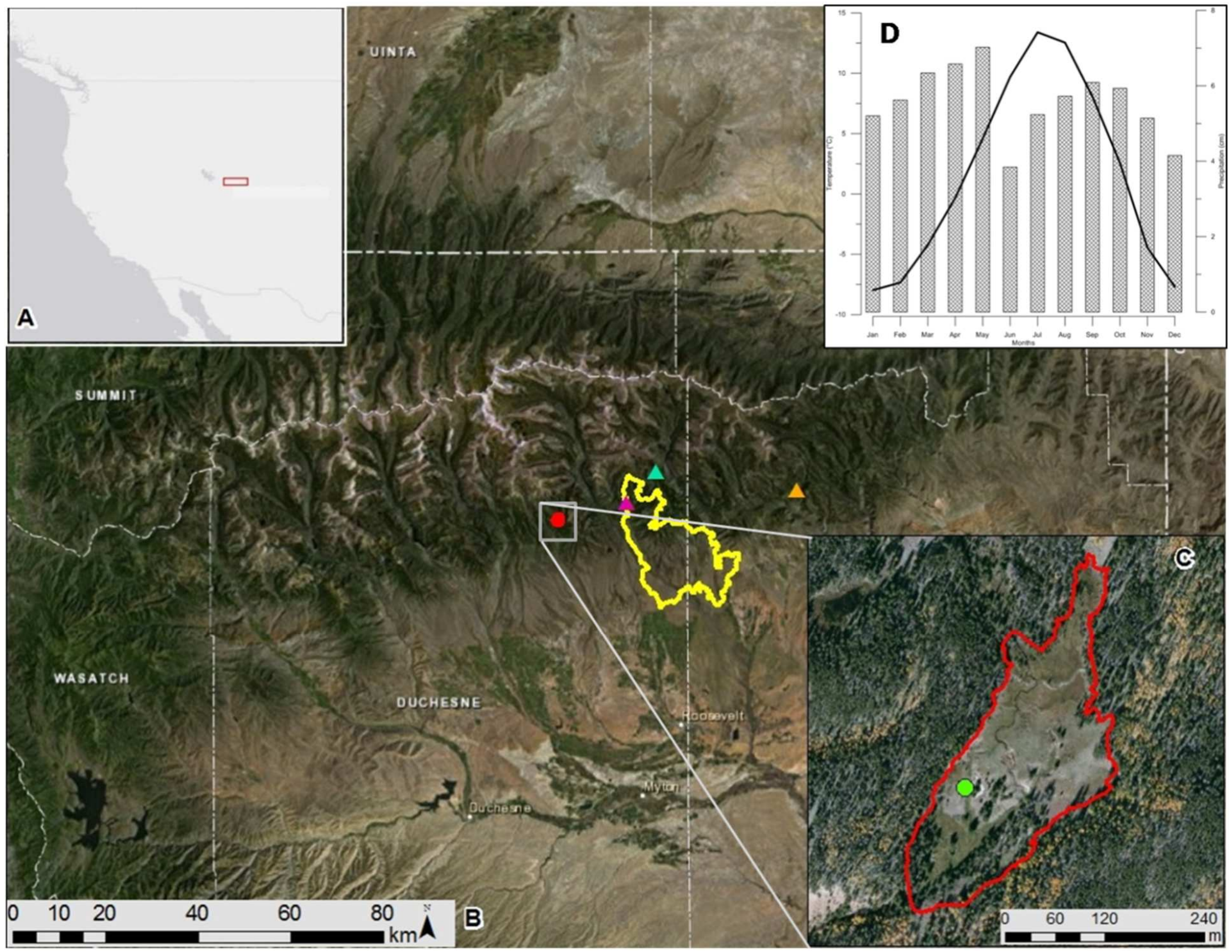

Figure 1. Location of study site. A) Showing location of Uinta Mountains; B) showing location of study site within the Uinta Mountains; and C) ESRI satellite imagery showing Dry Gulch Meadow, and location of sampling site. Also showing D) average monthly precipitation and temperature; and locations of Larvae Lake (green triangle), MUR (pink triangle), BRO (orange triangle), and 2007 Neola North Fire scar (yellow outline).

the 8.2 ka event, the Medieval Climate Anomaly (MCA), and the Little Ice Age (LIA). A second hypothesis is that fire frequency in montane ecosystems has remained consistent through time, with fire events occurring on average every few centuries. Although there has been a general increase in fire occurrence in the western United States in the last several decades linked to fire suppression and a warming climate (Westerling et al. 2006), I hypothesize that prior to these recent warming trends, fire activity likely remained consistent in mid-elevation forests during the Holocene. Research by Schoennagael et al. (2004) suggests this may be the case in sub-alpine and many mid-elevation mixed forests, where fire suppression activities have had negligible impacts during the 20th century. Finally, a third working hypothesis suggests that 20th-century management activities have impacted vegetation communities and fire regimes in the mid-elevation Uinta Mountains. These hypotheses will be tested by reconstructing the vegetation and fire history, including fire return intervals, from multiple proxies preserved in sediment archives. These results will be compared with fire-scarred tree-ring records and management practices.

This high-resolution (averaging ~20 years per 0.5-cm sample interval) study will establish significant knowledge in Uinta Mountains long-term ecology by analyzing multiple proxies collected from the Heller Lake watershed. This sampling resolution was possible because of the catastrophic draining of the lake basin and the recent exposure of lacustrine sediments.

CHAPTER 2

SETTINGS

Site Description

Heller Lake/Dry Gulch Meadow (HLDGM), Duchesne County, Utah (40.603889 °N -110.229167 °W, 2870 m) is located in Ashley National Forest, near the headwaters of Dry Gulch Creek, on the south side of the Uinta Mountains at about 2870 m in elevation, between the Uintah and Ouray Indian Reservation and High Uintas Wilderness Area (Figure 1). The meadow complex was recently formed by the draining of a moraine-dammed lake located about 0.65 km south of Heller Lake. The meadow is oval shaped, surrounded by steep terminal and lateral moraines on the east, south, and west sides and the slope of the mountain on the north side. The meadow has a surface area of approximately 2 ha, and an inflowing stream that separates into multiple channels before combining again into a single out-flowing channel. PRISM (2011) data indicate winter (December, January, February) and summer (June, July, August) precipitation totals of 14.98 cm and 14.82 cm, respectively, and average winter and summer temperatures of -7.66 °C and 11.33°C (Figure 1).

Modern vegetation communities within HLDGM are characterized by wet meadow species and montane forest species. Within the wet meadows, five species of sedges (Cyperaceae) dominate with lesser contributions from horsetails (Equisetaceae) and willows (Salicaceae). Seven species of meadow grasses (Poaceae), as well as mesic herbaceous members of the Asteraceae, Boraginaceae, Brassicaceae, Campanulacea, Caprifoliaceae, Caryophyllaceae, Chenopodiaceae, Fabaceae, Fumariaceae, Grossulariaceae, Juncaceae, Liliaceae, Onagraceae, Polygonaceae, Ranunculaceae, Rosaceae, Rubiaceae, Scrophulariaceae, and Violaceae families also occupy the wet meadow around HLDGM (see Table 1 for species information). The montane forest around the meadow is dominated by lodgepole pine (*Pinus contorta*), intermixed with Engelmann spruce (*Picea engelmanii*) and patches of quaking aspen (*Populus tremuloides*). The dominant arboreal vegetation and elevation suggest a moderate to high severity fire regime (Pyne et al. 1996).

Geologic Setting

The core of the east-west-trending Uinta Mountains exposes the Uinta Mountain Group (UMG), a thick Neoproterozoic siliclastic succession (Dehler & Sprinkel 2005). The UMG is overlain by Paleozoic sedimentary strata that are exposed on the flanks of the range, which has an anticlinal structure. The study site is located just north of the contact between the Uinta Mountain Group (Neoproterozoic), whose outcrop extends north toward the crest of the range and the Paleozoic sedimentary sequence (Bryant 1985).

The meadow is enclosed by recessional moraines formed during the Smiths Fork Glaciation (Munroe & Laabs 2009) (Oxygen Isotope stage 2, approximately 24 ka years (Martinson et al. 1987)), which is correlative with the Bull Lake glaciations in other parts of the Rocky Mountains. Deposits of the older Blacks Fork Glaciation are not preserved

Table 1. Botanical Survey of HLDGM area carried out in 2011. Species names following protocol of A Utah Flora (Welsh et al. 2008).

Family	Scientific Name	Family	Scientific Name
Asteraceae	*Achillea millefolium*	Liliaceae	*Allium brevistylum*
	Anaphalis margaritacea	Onagraceae	*Epilobium saximontanum*
	Antennaria corymbosa	Polygonaceae	*Acetosella vulgaris*
	Cirsium sp.		*Bistorta bistortoides*
	Erigeron flagellaris		*Bistorta viviparum*
	Erigeron ursinus		*Rumex salicifolius*
	Packera crocata	Pinaceae	*Abies lasiocarpa*
	Senecio multilobatus		*Picea engelmannii*
	Taraxacum officinale		*Pinus contorta*
Boraginaceae	*Mertensia ciliata*	Poaceae	*Agrostis scabra*
Brassicaceae	*Boechera stricta*		*Calamagrostis canadensis*
	Draba albertina		*Deschampsia cespitosa*
Campanulaceae	*Campanula rotundifolia*		*Elymus trachycaulus*
Caprifoliaceae	*Sambucus racemosa*		*Festuca ovina*
	Symphoricarpos oreophilus		*Poa pratensis*
Caryophyllaceae	*Cerastium arvense*		*Trisetum spicatum*
	Cerastium nutans	Ranunculaceae	*Ranunculus inamoenus*
	Silene drummondii		*Thalictrum sparsiflorum*
	Stellaria umbellata	Rosaceae	*Fragaria virginiana*
Chenopodiaceae	*Chenopodium atrovirens*		*Geum macrophyllum*
Cyperaceae	*Carex aquatilis*		*Potentilla diversifolia*
	Carex canescens		*Potentilla fruticosa*
	Carex microptera		*Rubus idaeus*
	Carex rossii		*Sibbaldia procumbens*
	Carex rostrata	Rubiaceae	*Galium bifolium*
Equisetaceae	*Equisetum arvense*	Salicaceae	*Salix planifolia*
Fabaceae	*Astragalus miser var. oblongifolius*	Scrophulariaceae	*Castilleja rhexifolia*
	Thermopsis montana		*Pedicularis groenlandica*
	Trifolium longipes		*Penstemon humilis var. humilis*
Fumariaceae	*Corydalis aurea*		*Penstemon strictus*
Grossulariaceae	*Ribes inerme*		*Veronica serpyllifolia*
Juncaceae	*Juncus arcticus*		*Veronica wormskjoldii*
	Juncus hallii	Violaceae	*Viola adunca*
	Luzula comosa		
	Luzula parviflora		

within the study area (Laabs & Carson 2005). The area was glaciated through the LGM and likely became ice-free 14 to 13 thousand years ago (Laabs & Carson 2005; Munroe & Laabs 2009). However, given the length of the record reported in this study, the meadow likely became ice-free earlier than this. The Smiths Fork Till within the meadow basin itself is overlain by Holocene lake sediments (Munroe & Laabs 2009), which are exposed at the surface and in stream-cut exposures. The meadow is currently being subjected to significant piping and subsidence; the overflow stream from Heller Lake disappears into a sink-hole like feature in the meadow floor and re-emerges approximately 15 m downstream.

CHAPTER 3

METHODS

Field Work

In July 2011, a 3.21-m-long core was collected from a stream headcut in the meadow; the three upper sections were collected as pedestal cores dug out of a pit (0-242.5 cm), and a final section (242.5-321 cm) was collected using a Livingstone corer. Each segment was wrapped in plastic wrap and aluminum foil. In August 2013, an additional sediment record was collected from Larvae Lake, 18 km northeast from HLDGM. A 1.4-m-core was collected near the depocenter of Larvae Lake from an anchored platform using a Livingstone corer. A 30-cm top core was also collected using a polycarbonate tube piston corer to capture the mud-water interface. Lithology of each drive was described in the field, and then wrapped in plastic wrap and aluminum foil. The top core was sampled contiguously in the field at 0.5-cm increments, which were placed in individual whirl-pak bags. All sediments were transported to the Garret Herbarium at the University of Utah and refrigerated prior to further analysis. Increment cores were also collected from *P. engelmanii* and *P. contorta* in the meadow and on the surrounding moraines to determine the length of time trees have occupied the former lake basin.

Chronology and Lithology

Due to the catastrophic draining of the lake in the early 1900s when the moraine dam failed, and the presence of disturbance factors such as cattle, the historical portion of the record has been washed away and/or compacted. Therefore, the top date of the core is not tied to the collection date of the core, but was instead interpolated from the rest of the dates and calculated to be 386 cal yr BP. To remedy the lack of historical sediment, the Larvae Lake top core was sampled for charcoal to create a 20th-century fire record. This record not only captures large modern fire events such as the 2007 Neola fire, but also overlaps the available tree-ring-based fire records for the area, and part of the HLDGM record. Heyerdahl et al. (2011) constructed a fire history study in Utah and eastern Nevada using fire-scarred trees to determine historical fire regimes and forest histories. Comparing the Heyerdahl et al. (2011) study with this research allows linking known fire events, such as those detected by analysis of fire-scarred trees, with peaks in sedimentary charcoal. Two study sites from Heyerdahl et al. (2011), Brownie Creek (BRO) and the central Uinta Mountains (MUR), are located near both Heller meadow and Larvae Lake (Figure 1). Fire-scarred tree-ring chronologies developed at BRO and MUR sites provide an independent age control on fire events.

Age-depth relationships for HLDGM were determined using ten AMS-^{14}C dates from bulk sediment, while age-depth relationships for Larvae Lake were determined using one AMS-^{14}C date from bulk sediment (Table 2). Radiocarbon dates were converted to calibrated years using CALIB 7.0 (Stuiver & Reimer 1993; Reimer et al. 2013) and the age-depth relationship was converted to calibrated years before present (cal yr BP; AD 1950 = year 0) with a smoothing spline for the entire record (Figure 2).

Table 2. Radiocarbon dates for HLDGM, Larvae Lake, and Carson 2003 PhD dissertation. An age model for HLDGM and Larvae Lake was constructed using a smoothing spline.

Core	Depth (cm)	Lab No.	Material	13C/12C	^{14} C Age	CAL BP age range (2σ)	Cal BP median age
HLDGM	5.5 – 6	371377	Organic sediment	-27.1 o/oo	640 ± 30	550 – 670	599
HLDGM	15 – 15.5	334172	Organic sediment	-25.9 o/oo	1470 ± 30	1300 – 1410	1355
HLDGM	30 – 30.5	324081	Plant material	-24.7 o/oo	1690 ± 30	1530 – 1690	1593
HLDGM	75 – 75.5	334173	Organic sediment	-25.8 o/oo	4590 ± 30	5150 – 5440	5312
HLDGM	98 – 98.5	334176	Organic sediment	-26.1 o/oo	5390 ± 30	6120 – 6280	6217
HLDGM	148 – 148.5	334175	Plant material	-24.9 o/oo	5740 ± 40	6440 – 6650	6538
HLDGM	190 – 190.5	371378	Organic sediment	-24.2 o/oo	6880 ± 40	7660 – 7790	7712
HLDGM	248 – 248.5	362249	Organic sediment	-25.3 o/oo	9160 ± 40	10230 – 10480	10318
HLDGM	278 – 278.5	334174	Plant material	-26.0 o/oo	9720 ± 50	10890 – 11230	11162
HLDGM	317 – 317.5	334171	Organic sediment	-22.9 o/oo	12010 ± 50	13780 – 13960	13864
Larvae Lake top core	29.5 – 30	362255	Plant material	-24.4 o/oo	600 ± 30	542 – 573	604
Larvae Lake C4D1	30-30.1	362251	Organic sediment	-30.7 o/oo	1260 ± 30	1087 - 1281	1218
Carson 2003†	37	BETA-203233	Charcoal	-22.3 o/oo	1210 ± 40	1260 – 1060	1160
Carson 2003†	122.5	BETA-163194	Wood	-25.0 o/oo	5390 ± 80	6310 – 5990	6150
Carson 2003†	157	BETA-167778	Leaves	-25.0 o/oo	6570 ± 80	7585 – 7320	7452.5
Carson 2003†	198.5	BETA-163193	Plant material	-25.0 o/oo	8340 ± 70	9490 – 9130	9310
Carson 2003†	217	BETA-167777	Leaves	-25.0 o/oo	8730 ± 150	10185 – 9500	9842.5
Carson 2003†	253	BETA-163192	Wood	-25.0 o/oo	9980 ± 100	11825 – 11215	115230
Carson 2003†	304	BETA-203234	Conifer	-22.4 o/oo	10990 ± 50	13000 – 12860	12930

†dates not used in this chronology

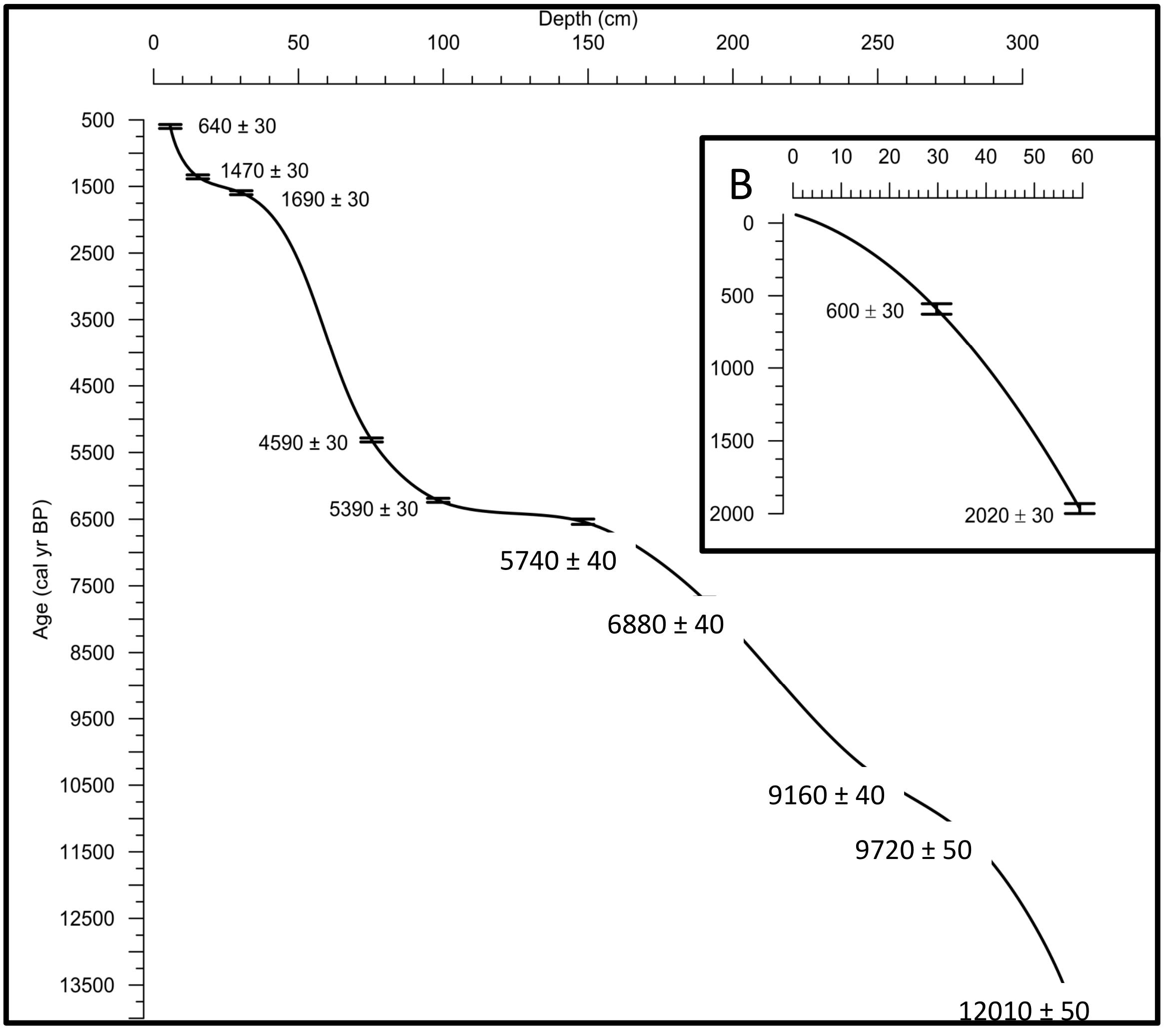

Figure 2. Age-depth model for HLDGM and Larvae Lake (inset). Age model depicts calibrated AMS 14C ages vs. depth.

The interpolated basal age of the record is 14,114 cal yr BP.

The pedestal cores were cut in half lengthwise, with one half being preserved for archive and the other half being cut in half lengthwise again for magnetic susceptibility and subsampling. The 5-cm-diameter Livingston core was split in half, with one side preserved for archive and the other used for subsampling. The cores were scanned and the images stitched together to create a seamless picture of each core segment.

The core was visually inspected for changes in lithology and colour using a Munsell soil colour chart, and separated into 19 stratigraphic sections. Each section was described for colour, sediment texture, macrofossils, and any other features. Most of the sediment sequence is composed of massive sections of silty clay (0-74 cm) interspersed with clay-rich mottles in the upper sections of the core (74 cm-161 cm), and fine-gained light-coloured clay layers occurring in the lower sections of the core, from 161 cm to 320 cm. Obvious laminations at the base of the core are likely indicative of a deeper lake system in the past. Light-coloured clay layers may indicate oligotrophic lake conditions, as there was little charcoal or organic material within these units. Seeds and macrofossils appear sporadically within the core, with the majority between 212.5 cm to 275 cm, appearing with much lower concentration in the clay sections than within the silty-clay sections. Thin, averaging <0.5 cm in thickness, organic-rich layers, occurring between 161-188 cm, 197-204 cm, and 212.5-238 cm, likely indicated periods of increased productivity within the lake, or increased influx of organic material into the lake.

Charcoal Analysis

Macroscopic charcoal (>125 μm) has been widely used as a proxy for local fire as it does not travel far from the fire source (Whitlock & Larsen 2001). The core was sampled in contiguous half-centimeter increments beginning at the surface for evaluating charcoal abundance through time. Five milliliters of 10% potassium hydroxide was added to samples of either 1 CC or 0.25 CC and soaked in a hot water bath for twenty to thirty minutes. The samples were then rinsed through a 125-micrometer screen and counted using a dissecting scope at 40X magnification. CHAR Analysis software (Higuera 2010) was used to statistically determine peak occurrence for local fire history reconstruction. The charcoal accumulation rate (CHAR, particles cm^{-2} yr^{-1}) was calculated for the entire record. For Dry Gulch Meadow, a lowess smoother robust to outliers was applied using a 200-year window to determine background charcoal levels. Peaks were identified using a Gaussian Mixture model and a local threshold. For Larvae Lake, a lowess smoother that was robust to outliers was applied using a 150-year window to determine background charcoal levels. Peaks were identified using a Gaussian Mixture model with a locally defined threshold and a 500-year frequency.

Pollen Analysis

Vegetation history was examined by studying pollen assemblages at 5-cm intervals for the length of the core. Sediment samples of 1.0 cubic centimeter were processed for fossil pollen and counted using standard palynological methods (Faegri et al. 1989). Samples were collected every 5 cm beginning at the surface. An additional hydrofluoric acid treatment was performed due to the high concentration of silicates in many of the samples. The spore Lycopodium was used as the tracer. The samples were treated with safranin strain and stored in silicon oil. Pollen grains from the processed samples were mounted on slides and counted using light microscopy at 400x magnification. A minimum of 300 pollen grains were counted for each sample. Pollen was identified to the lowest taxonomic rank possible using reference slides for the Garrett Herbarium and published pollen keys (Kapp et al. 2000). There are two subgenera of pines; haploxylon pines have a single fibrovascular bundle in the leaf cross-section while diploxylon pines have two fibrovascular bundles in the leaf cross-section (Richardson 1998). With the exception of limber pine (*Pinus flexilis*), haploxylon pines in northern Utah are typically found at lower elevations in the southern and western areas of the state. Pinyon pine (*Pinus edulis)* occurs in the valleys around the Uintas, but not at high elevations (U.S. Geological Survey 1999; Shaw & Long 2007). While the distribution of limber pine includes the Uinta Mountains, it is not a dominant species there, occurring primarily in the Wasatch Range (Mauk & Henderson 1984). Based on the modern phytogeography/distribution of pines in the Uinta Mountains (Shaw & Long 2007), haploxylon and diploxylon pines were not separated out as any haploxylon pines were most likely the result of long distance transport and would not be representative of an actual haploxylon population in the area. Pollen percentage data are presented as zonal averages unless otherwise noted. Pollen zones were calculated using CONISS (Grimm 1987); these same zone boundaries are used for organizing the discussion. Pollen influx was also calculated for each sample to determine the rate of pollen production per unit of time (Fall 1992).

Loss-on-Ignition

Loss-on-Ignition (LOI) determines the productivity of a lake by comparing the percentage of organic carbon and carbonates in the sediments (Heiri et al. 2001; Tingstad et al. 2011). The core was sampled in contiguous half centimeter increments with sample sizes of 1 cubic centimeter (approximately 1 g). Samples were dried in a muffle furnace at 70 °C for 12 hours, and then burned at 550 °C for 2 hours, and at 1000 °C for 2 hours. Samples were allowed to cool and weighed between each heating to determine the change in mass. The 550 °C burn removed organic carbon; the 1000 °C burn removed inorganic carbon (Dean 1974).

Magnetic Susceptibility

Magnetic susceptibility measures how easily sediments take a magnetic charge, and can indicate the input of allochthonous materials into the lake environment, typically through erosion and stream transport (Thompson et al. 1975). Magnetic susceptibility was completed using a Bartington MS2C Core Logging sensor and measured in SI units. The entire core was run through the sensor in segments at half-centimeter increments; the bottom Livingston core was processed before being split, the upper three slab cores were split and had the corners rounded before being run through the sensor. Changes in SI in a core are relative to the core being processed. As each core segment was processed individually, there is some noise in the record where the different processing runs of the cores were seamed together.

CHAPTER 4

RESULTS AND DISCUSSION

Zone 1 Early Post-Glacial (>14,000-13,600 cal yr BP)

During the glacial period, the North American ice sheets and the Arctic sea ice were at their maximum extent and permafrost was widespread (Clark et al. 2012). There was a large glacial anticyclone over the Laurentide Ice sheet causing the interior of North American to be colder and dryer than present (COHMAP 1988). In the western United States, alpine glaciers occupied most high-elevation mid-latitude mountains, including the Uinta Mountains (Munroe et al. 2006; Refsnider et al. 2008), and most plant communities were likely displaced to lower elevations (Williams et al. 2004).

At HLDGM, arboreal (35%) and shrub (30%) taxa dominated the pollen assemblage (Figure 3), closely followed by herbaceous pollen types (22%). Relatively low aquatic pollen types, compared to later times, suggest glacial conditions were generally too dry to support closed-canopy forests and mesic communities. Arboreal pollen is dominated by pine, oak, and spruce species (*Pinus*, 20%; *Quercus*, 4.2; *Picea*, 4.6%), shrub pollen is dominated by sagebrush, rose, and amaranth species (*Artemisia* 18%; Rosaceae 5%; Amaranthaceae 4.5%). The herbaceous assemblage is dominated by grasses, ragweed, and members of the mustard family (Poaceae 13%; *Ambrosia* 2.7%; Brassicaceae 2.6%). Pollen accumulation rates (PAR) (Figure 4) were similar for trees

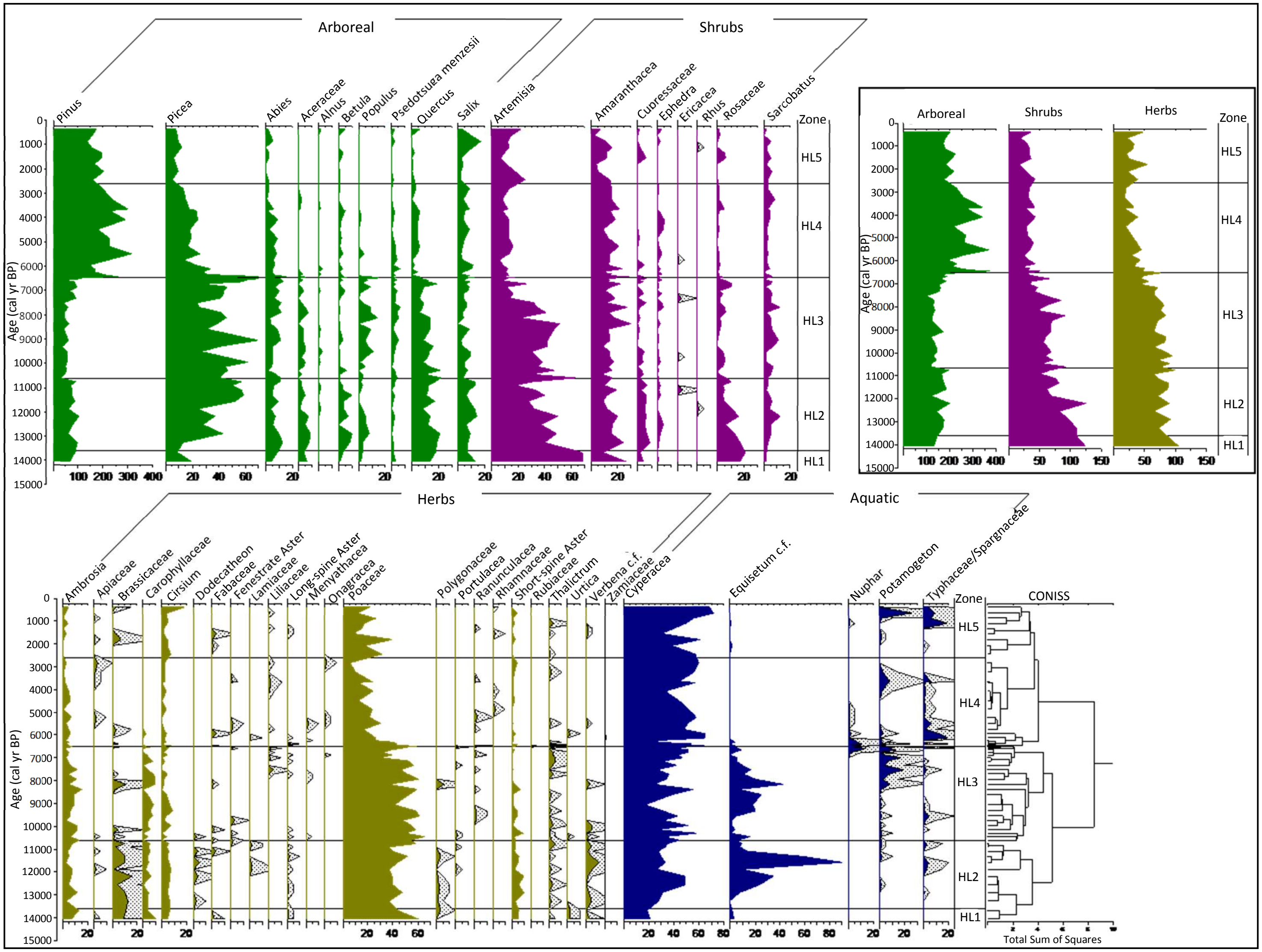

Figure 3. Pollen Percentages with CONISS showing species for arboreal taxa (green), shrub taxa (purple), herb taxa (yellow), and aquatic taxa (blue). Summary diagram (inset) showing percent of total arboreal, herb, and shrub species.

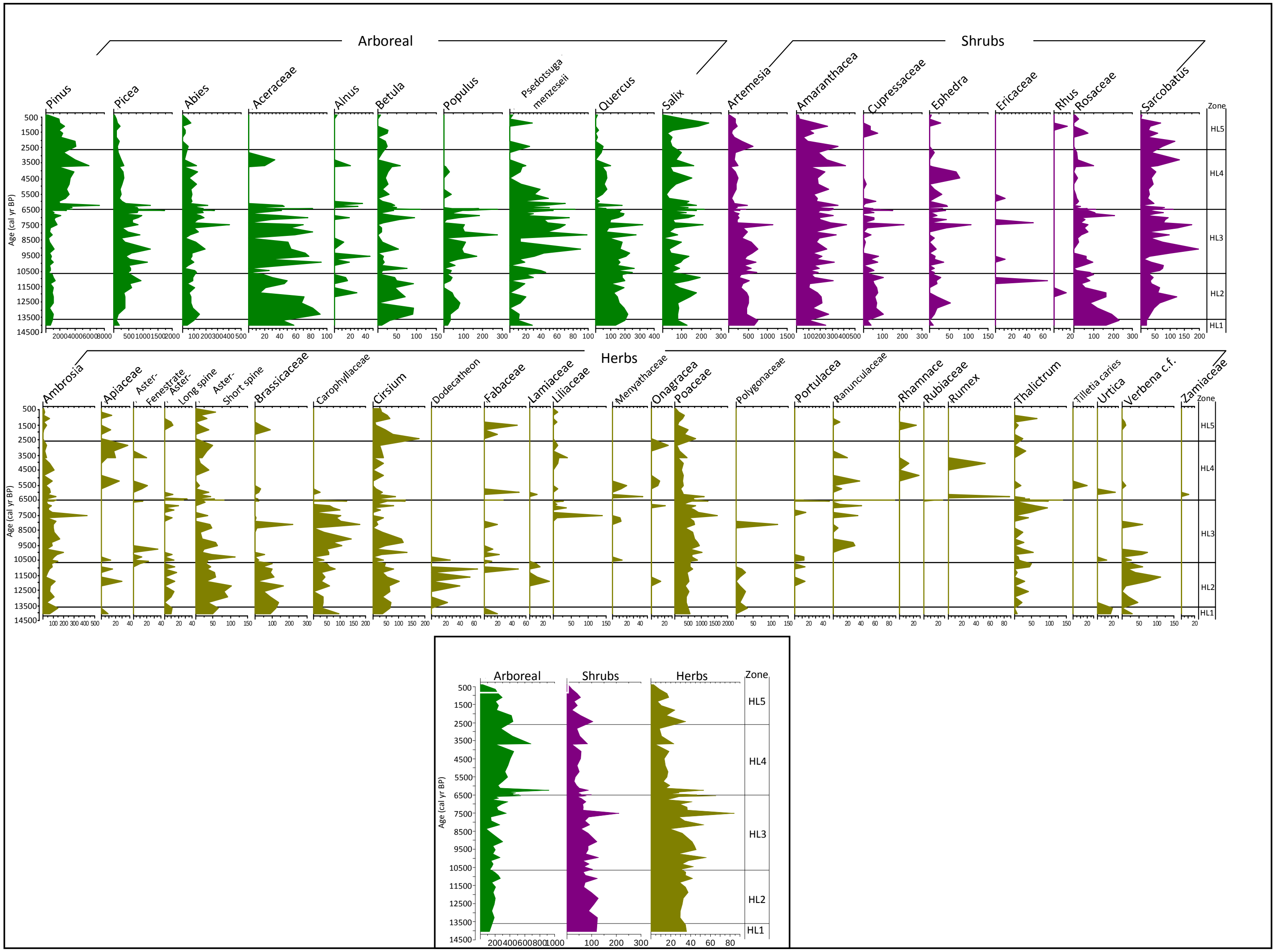

Figure 4. Pollen Accumulation Rates (PAR) showing species for arboreal taxa (green), shrub taxa (purple), and herb taxa (yellow). Summary diagram (inset) showing percent of total arboreal, herb, and shrub species.

and shrubs, averaging ~155 grains cm^{-2} yr^{-1}each, while herbaceous taxa contributed to less than 2% of the total PAR. Low LOI values (Figure 5) for both percent organics and percent carbonates suggest a period of low productivity around HLDGM. This assemblage from HLDGM suggests an open dry woody-shrub steppe with few herbaceous taxa (Fall 1992).

The cold, dry glacial climate likely limited fire activity with only three fire episodes detected prior to 13,600 cal yr BP. As global and regional climates warmed, vegetation abundance (e.g., fuels) increased on the landscape. Fires occurred every 150-200 years, but were generally low magnitude events, as suggested by the low charcoal flux, ranging from 7.31 to 0 particles cm^{-2}year^{-1}. The largest peak magnitude in charcoal occurred at the end of the glacial period, 13,600 cal yr BP, registering a relatively small peak of 26.69 cm^{-2}peak^{-1}, suggesting fire activity was both infrequent and of low severity (Figure 6). Elevated magnetic susceptibility (Figure 5) values (>3.3 SI) were likely caused by glacial scouring and erosion as alpine glaciers retreated at higher elevations, increasing the inputs of allochthonous materials (Thompson et al. 1975) into HLDGM.

<u>Zone 2 Late Post-Glacial (13,600 – 10,650 cal yr BP)</u>

Following deglaciation, there was a general warming of the climate as summer insolation in the Northern Hemisphere increased (COHMAP 1988; Clark et al. 2012) reaching an insolation maximum by 11,000 cal yr BP for 45° latitude (Berger & Loutre 1991). As the Laurentide ice sheet decreased in size and thickness and the jet stream gradually migrated northward in response to the diminished height of the ice sheet, alpine glaciers retreated in the western United States and plant communities began adjusting

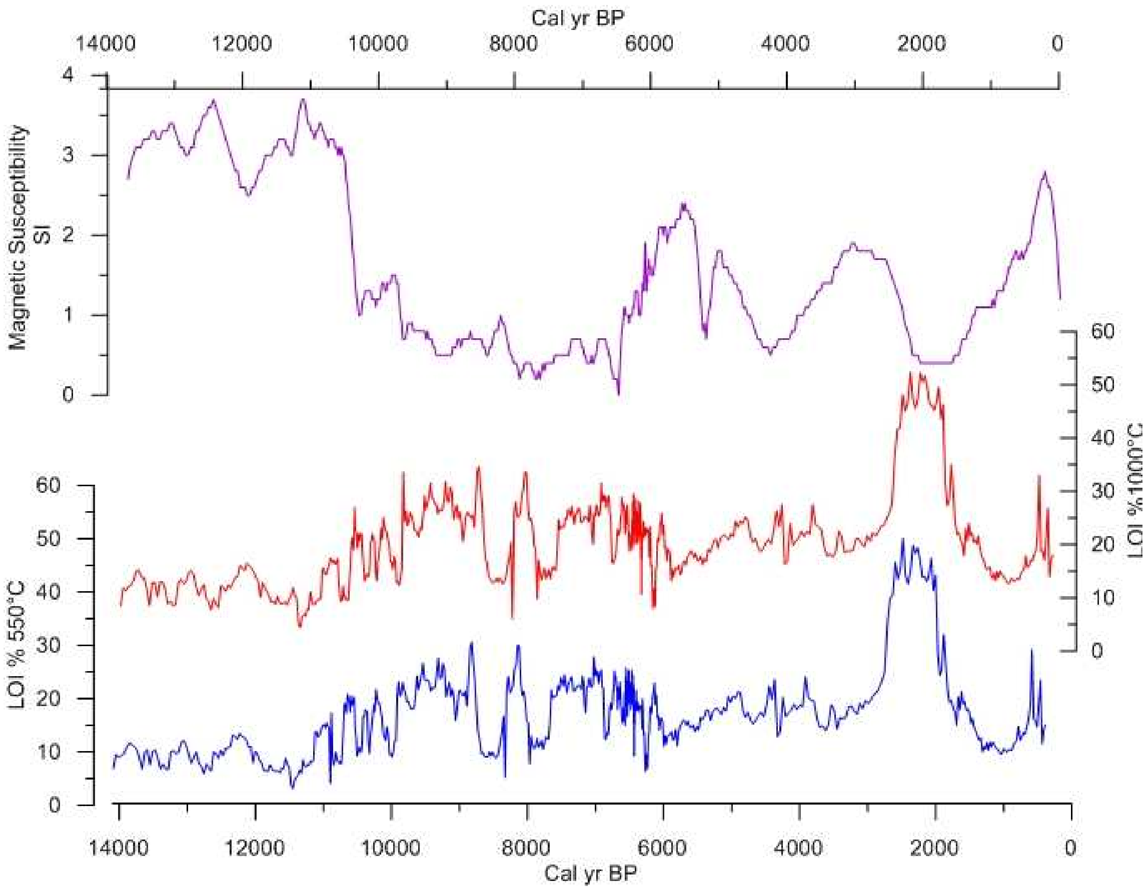

Figure 5. Magnetic susceptibility (purple line), loss-on-ignition 550 °C burn (blue line), loss-on-ignition 1000 °C burn (red line).

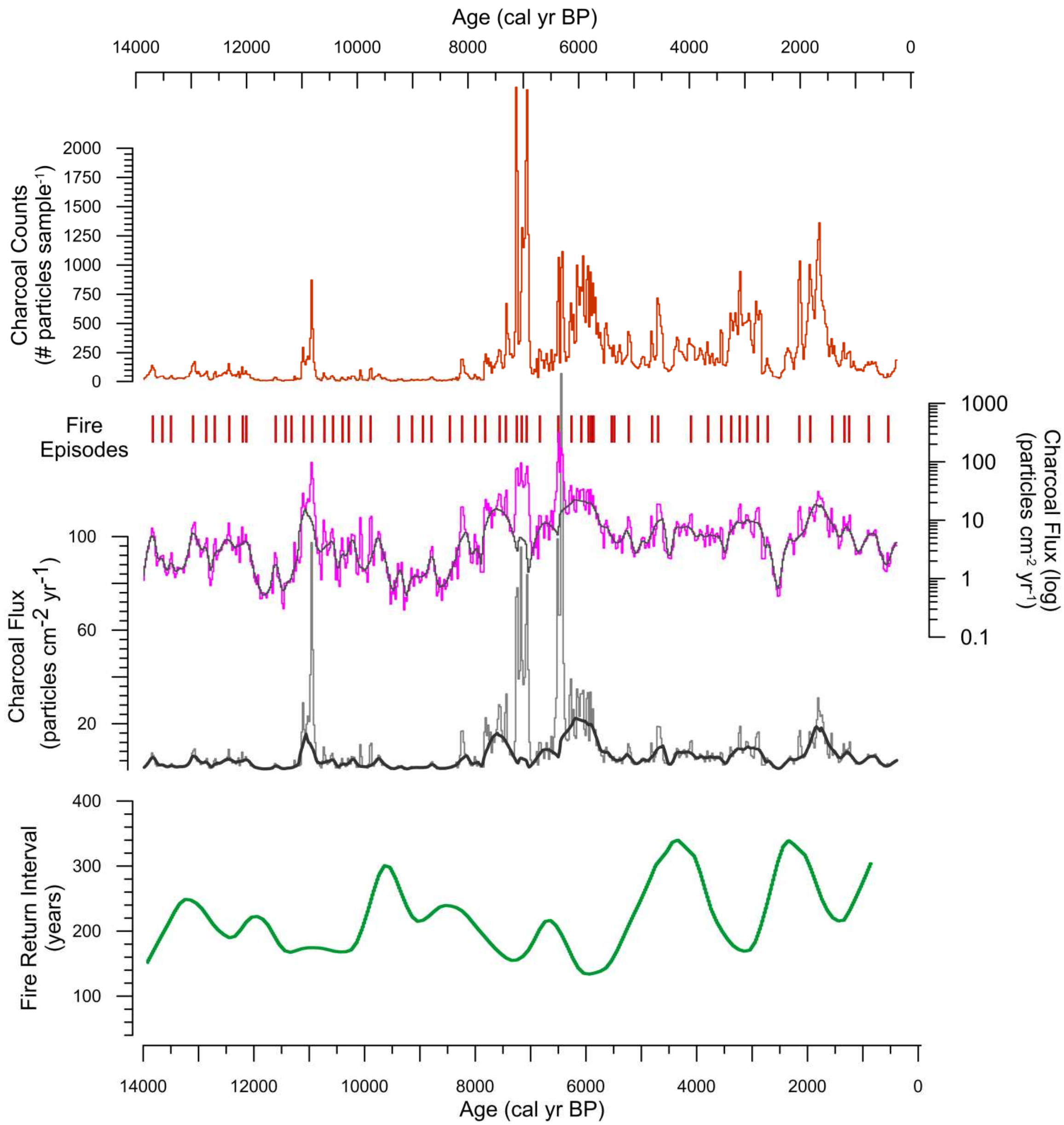

Figure 6. Sedimentary charcoal record for HLDGM showing raw charcoal counts, fire episodes, charcoal flux on a log scale and standard scale, and the fire return interval.

their ranges (Williams et al. 2004). The jet stream was likely stronger than it is in modern times and easterly wind anomalies gradually diminished as westerly winds strengthened across the western United States (COHMAP 1988). The overall climate at this time continued to be cooler than modern with only small increases in arboreal forests (42% of pollen sum) and shrub (21%) and herb assemblages (19%) at HLDGM (Figure 3). The slight increase from glacial times in aquatic pollen types suggests increased water availability, either through changes in seasonal precipitation or increased melt-water from warmer summers. Arboreal, shrub, and herbaceous pollen continues to be dominated by pine, spruce, and oak species (*Pinus*, 19.3%; *Picea*, 10.7%; *Quercus*, 3.9%), sagebrush, amaranth, and rose species (*Artemisia* 9.9%; Amaranthaceae, 3.9%; Rosaceae 2.3%), and grasses, ragweed, and members of the mustard family (Poaceae, 11.4%; *Ambrosia*, 1.79%; Brassicaceae, 1.78%). Pollen production (Figure 4) for arboreal species increased from 155 to 193 grains cm^{-2} yr^{-1}, but decreased for both shrubs and herbs to 2% and 1% of the total PAR, respectively. LOI values (Figure 5) for both percent organics and percent carbonates are higher than during the glacial, but still lower than the rest of the record, suggesting continued low productivity around HLDGM. The assemblage suggests the establishment and expansion of spruce parkland vegetation. As pine, spruce, and fir expanded into the HLDGM, the cooler-than-present climate (Tingstad et al. 2011) was likely punctuated by abrupt cooling, including the YD event, between 12,700 – 11,900 cal yr BP (Alley 2000). This cooling event likely impacted many mid-latitude terrestrial ecosystems, and may have altered species dynamics and the fire activity at HLDGM (Figure 6). For example, fire frequency increased from 4 events/1000 years to 6 events/1000 years (Fire Return Interval or FRI 170-250 yrs) (Figure 7). Charcoal flux

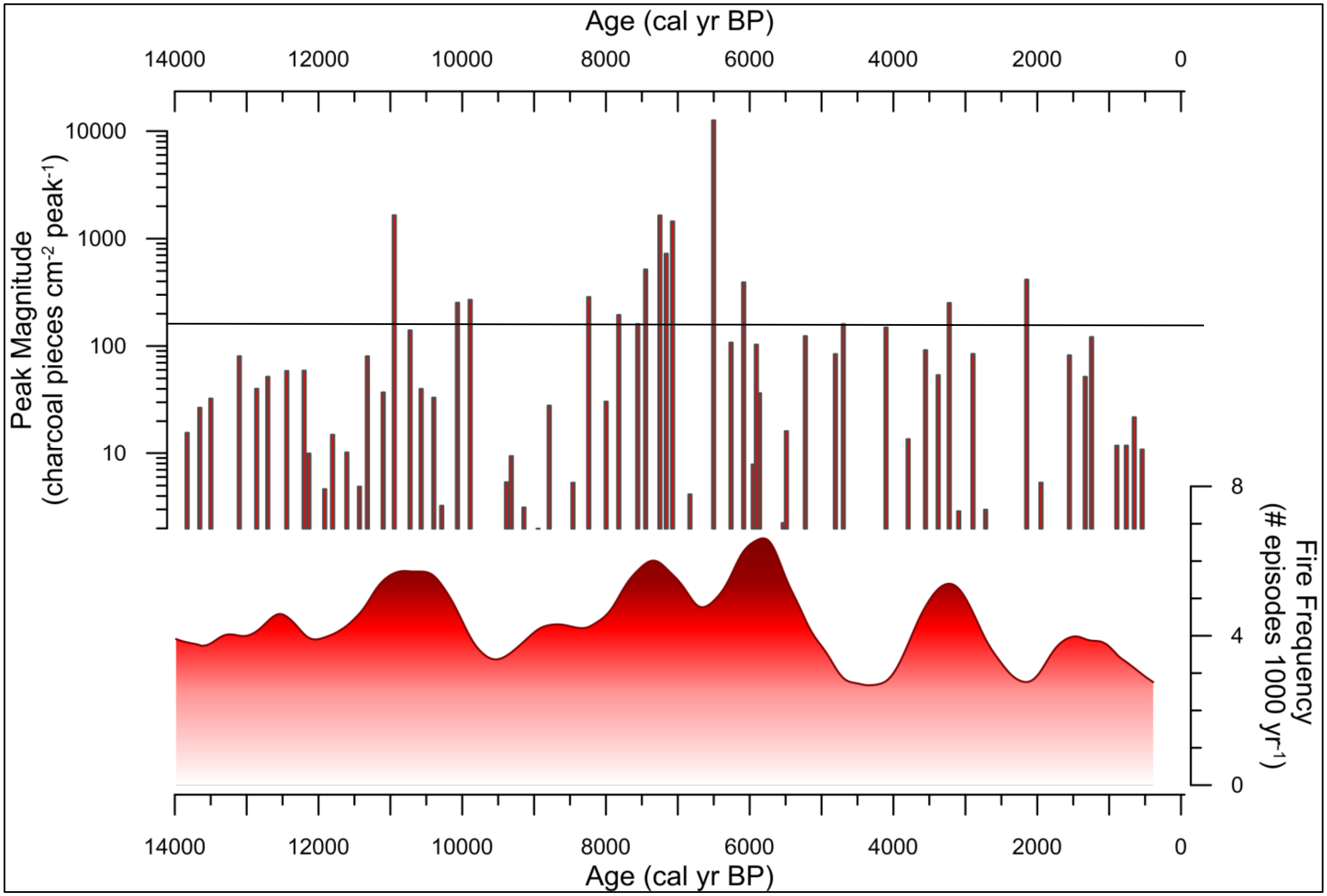

Figure 7. Histogram showing peak magnitudes of all the fires and fire frequency at HLDGM. The blue line on the histogram is the peak magnitude of the Neola fire at Larvae Lake at 170 cm^{-2}peak^{-2}. There were at least 16 fires that were as big as or bigger than the 2007 Neola fire.

indicated that with the exception of a large fire episode occurring approximately 10,950 cal yr BP, most were generally low magnitude events, ranging from 0.31 to 28.9 particles $cm^{-2}year^{-1}$. Of the 15 fire episodes detected, the largest had a peak magnitude of 1648 $cm^{-2}peak^{-1}$and occurred at approximately 10,950 cal yr BP, during a warmer period following YD. Increased magnetics values (Figure 5) before and after the YD (3.7 SI), and a decrease (2.5 SI) within the YD suggest a decrease in erosion activity during the YD time period. Tree and herb pollen decreased slightly during the YD, while shrub pollen increased slightly, suggesting a contraction or at least halt in the expansion of spruce parkland and a return to steppe conditions during the YD.

Zone 3 Early Holocene (10,650 – 6,500 cal yr BP)

Increasing Northern Hemisphere summer insolation during the early Holocene continued to decrease the size and height of the Laurentide ice sheet, supporting the northward migration of the jet stream; summer temperatures in the Northern Hemisphere tended to be warmer than present (COHMAP 1988). Although summer insolation became a dominant climate driver, the presence of the continental and alpine glaciers continued to affect local and regional climate (COHMAP 1988; Mayewski 2004). Landscapes adjacent to alpine glaciers, including HLDGM, were generally kept cooler and likely wetter than areas more distant from the ice. While arboreal forests continued to gradually increase (44% of pollen sum), herbaceous taxa stayed the same (19%), and shrubs decreased (16%) (Figure 3). Increases in aquatic pollen types further suggest the general increase in available moisture. Arboreal pollen continued to be dominated by pine, spruce, and oak species (*Pinus*, 19.8%; *Picea*, 13.4%; *Quercus* 3.3%), dominant shrub and herb pollen types including sagebrush, amaranth, and rose continued with increased abundance of greasewood species (*Artemisia*, 8.3%; Amaranthaceae, 4.6%; *Sarcobatus*, 1.4%). Grasses, ragweed, and members of the pink family also increased abundance (Poaceae, 15%; *Ambrosia*, 2%; Caryophyllaceae, 1%). Pollen production (Figure 4) for arboreal species increased from 193 to 227 grains cm^{-2} yr^{-1}, shrubs comprised 2% and herbs 1% of total PAR. The expansion of *Picea* as well as shrubs and herbs during the early Holocene suggests open spruce parkland vegetation (Fall 1992; Munroe 2003). Immediately following the 8.2 ka event (Alley & Agustdottir 2005; Ellison et al. 2006), during which arboreal species drop off, *Picea* expands while both Poaceae and *Artemisia* decrease, suggesting further expansion of spruce forests as temperature or moisture increased. The increased abundance of greasewood pollen suggests that lower elevation areas were dryer and/or warmer (Minckley et al. 2008). Increasing LOI values (Figure 5) during Zone 3 also suggest increasing productivity around HLDGM, further supporting early Holocene warming (Tingstad et al. 2011). The draining of glacial Lake Ojibway-Agassiz that was responsible for the 8.2 ka event (Ellison et al. 2006) caused Northern Hemisphere cooling, similar to that during the YD event, but likely half the magnitude (Alley & Agustdottir 2005; Mayewski 2004). The response of the 8.2 ka event in the Uinta Mountains is observed by the expansion of spruce at the expense of other tree and shrub communities. Immediately following the 8.2 ka event, fire becomes a more active disturbance agent with some of the largest variations in charcoal flux of the entire record (Figure 6). Between 10,600 and 6,500 cal yr BP, charcoal flux ranges from 0.29 to 98.99 particles $cm^{-2}year^{-1}$, with the greatest increases occurring after 7800 cal yr BP, several centuries after the 8.2 ka event. From about 9,600 – 8,300 cal yr BP, HLDGM experienced infrequent fires with mixed severity, but the magnitude and severity of fires increased dramatically between 7,800 – 6,000 cal yr BP with charcoal peak magnitudes exceeding 12,500 $cm^{-2}peak^{-1}$ at 6,500 cal yr BP. Fire frequency increased to the most frequent of any other time in the record. The transition between the early and middle Holocene is the largest change of vegetation at HLDGM, when *Pinus* increases dramatically at the expense of *Picea* (except during the 8.2 ka event), *Artemisia,* and Poaceae, signaling the beginning of transition into a different dominant vegetation community.

Zone 4 Middle Holocene (6,500 – 2,600 cal yr BP)

Climate during the middle Holocene was primarily driven by summer insolation and general solar variability (Mayewski et al. 2004), and summer temperatures continued to increase in the southwestern U.S. according to Viau et al. (2006). The Laurentide Ice sheet had completely disappeared and conditions throughout the interior of North American were drier (COHMAP 1988). Arboreal pollen, dominated by pine, spruce, and willow species (*Pinus*, 53.8%; *Picea*, 7.2%; *Salix* 1.5%), continued to increase and reached its peak (66%) while the significant decrease in herb pollen (8.7% from 16%) and shrub pollen (8.65% from 19%) indicates the establishment and expansion of pine forest at HLDGM (Munroe 2003) (Figure 3). Shrub pollen is dominated by amaranth, sagebrush, and greasewood species (Amaranthaceae, 3.7%; *Artemisia*, 2.9%; *Sarcobatus*, 0.88%), and herb pollen is dominated by grass, ragweed, and thistle species (Poaceae, 6.5%; *Ambrosia*, 0.95%; *Cirsium* 0.54%). Pollen production (Figure 4) for arboreal species doubles from 227 to 408 grains cm^{-2} yr^{-1}, while shrub and herb species each make up less than 1% of the total PAR. Although global climate was drier than the late Holocene, vegetation communities, including aquatics at HLDGM, suggests sufficient moisture for the continued presence of wet meadows and small lakes interspersing the pine forest.

Warming climate likely led to the migration of vegetation zones upwards in elevation. As *Pinus* became more common in the HLDGM area, fire activity also appears to increase (Figure 8). Around 6,600 cal yr BP, *Pinus* pollen begins a dramatic increase along with a large increase in charcoal flux, as *Picea* greatly decreases. As fire activity begins to decrease around 6,400 cal yr BP, *Pinus* has been established as the dominant vegetation type. The vegetation conversion from spruce parkland to pine forest impacted the fire regime (Figure 6) by lengthening the fire return interval to 134-340 yrs. Charcoal flux (ranging from 1.17-315.81 particles $cm^{-2}year^{-1}$) and the increased FRI suggest that fires became less frequent and likely more severe, common to lodgepole pine forests today (Lotan et al. 1985).

Zone 5 Late Holocene (2,600 cal yr BP- Present)

During the late Holocene, the jet stream began to behave similarly to present, being positioned well to the north in the winter and governing the locations of storm tracks in the western U.S. The Atlantic and Pacific subtropical high pressure systems dominate summer circulation while the Aleutian and Icelandic low pressure systems influence winter circulation. Summer temperatures decreased relative to those of the middle Holocene as summer insolation attenuated toward present (COHMAP 1988). The Medieval Climate Anomaly (MCA), occurring between 1,000-700 cal yr BP, and the

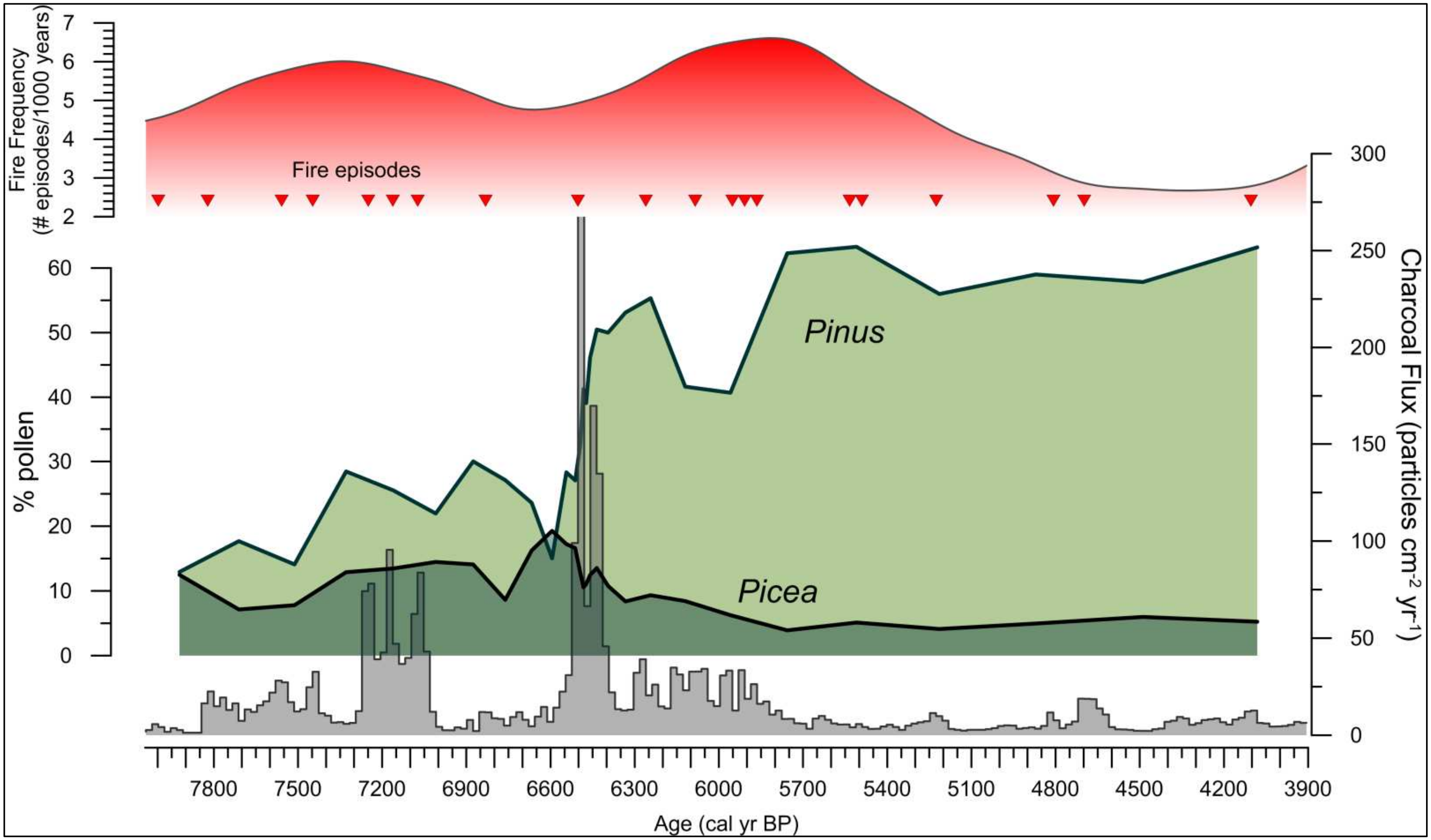

Figure 8. Close-up of early-to-mid-Holocene transition, showing fire frequency, fire episodes, and fire flux plotted against percent of *Pinus* and *Picea* pollen.

Little Ice Age (LIA), occurring between 550-250 cal yr BP, were warm and cold climate events, respectively, during the late Holocene (Mann et al. 2009). The MCA exhibited North Atlantic Oscillation-like conditions while during the LIA, more La Nina-like conditions persisted (Mann et al. 2009). According to tree-ring-based temperature reconstructions, the MCA has been considered a period of sustained positive mode of the North Atlantic Oscillation (NAO) with anomalously stronger-than-average high pressure over the Azores and weaker-than-average low pressure over Iceland in the North Atlantic. During the LIA, sustained La Nina-like conditions in the topical Pacific would have produced a pattern of strong cooling in the east and warming in the west (Graham et al. 2007; Mann et al. 2009; Trouet et al. 2009).

A persistent NAO positive mode may have resulted in warmer and drier conditions at HLDGM while a persistent La Nina-like condition may have led to cooler and potentially wetter conditions. However, reconstructed summer Palmer Drought Severity Index (PDSI) of the Uinta Mountain region (MacDonald & Tingstad 2007) and tree-ring-based streamflow reconstructions for Ashley Creek suggest that the peak of the LIA (1741-1897 AD) experienced warm/dry conditions with very little glacial activity (Carson & Munroe 2005). Although this is opposite of the expected ENSO/La Nina pattern, Larvae Lake fire episodes during the LIA are likely related to these warmer/drier conditions. Arboreal pollen (Figure 3) at HLDGM continues to be dominated by pine, spruce, and willow species (*Pinus*, 53.4%; *Picea*, 2.5%; *Salix*, 2%), and comprises the majority (59.5%) of the total pollen percentage. Herbs (6.9%) and shrubs (9.5%) increased slightly from the middle Holocene; herbs are dominated by members of the grass, thistle, and ragweed families (Poaceae 6.4%; *Cirsium* 1.5%; *Ambrosia* 0.57%), and shrubs are dominated by sagebrush, amaranth, and greasewood species (*Artemisia*, 4.5%; Amaranthaceae, 2.8%; *Sarcobatus*, 0.98%). Pollen production (Figure 4) for arboreal species decreases slightly from 408 to 361 grains cm^{-2} yr^{-1}, while shrubs and herbs increase to 2% and 1% of the total PAR, respectively.

Fire activity (Figure 6) decreases relative to the rest of the Holocene during the last 2600 years, with 9 fire episodes or 1 fire episode every ~275 years. Charcoal flux ranged from 0.50 – 31.01 particles $cm^{-2}yr^{-1}$, and the largest peak magnitude episode of 415.5 $cm^{-2}peak^{-1}$ occurred around 2146 cal yr BP. In general, fire episodes in the late Holocene become fewer, and peak magnitudes become smaller. There was a small increase in fires around the time of the MCA, which is also recorded as an increase in magnetic susceptibility (Figure 5). This rise in magnetics is likely linked to increased fire activity or greater erosion within the watershed. As the catastrophic failure of the moraine likely eroded the mud-water interface, it was necessary to look at the Larvae Lake charcoal record and the Heyerdahl et al. (2011) dendro record to explore potential overlap with the HLDGM record. The HLDGM record overlaps the Larvae record (Figure 9) for about 200 years (575 - 325 cal yr BP), and the Heyerdahl et al. dendro record overlaps for about 75 years (450 – 375 cal yr BP). The last fire episode in the HLGDM record is 10.79 $cm^{-2}peak^{-1}$ and occurs at 540 cal yr BP (1410 AD). The Larvae Lake charcoal shows six distinct fire episodes, the largest at -57 cal yr BP that we attribute to the 2007 Neola fire that burned within 3 km near the lake. Other fire episodes date approximately to 69 cal yr BP (1881 AD), 179 cal yr BP (1771 AD), 212 cal yr BP (1738 AD), 267 cal yr BP (1683 AD), and 465 cal yr BP (1485 AD), with the 465 cal yr BP fire episode being the second largest of the record. The earlier fire episodes, in the late 1880s and 1700s, are coeval

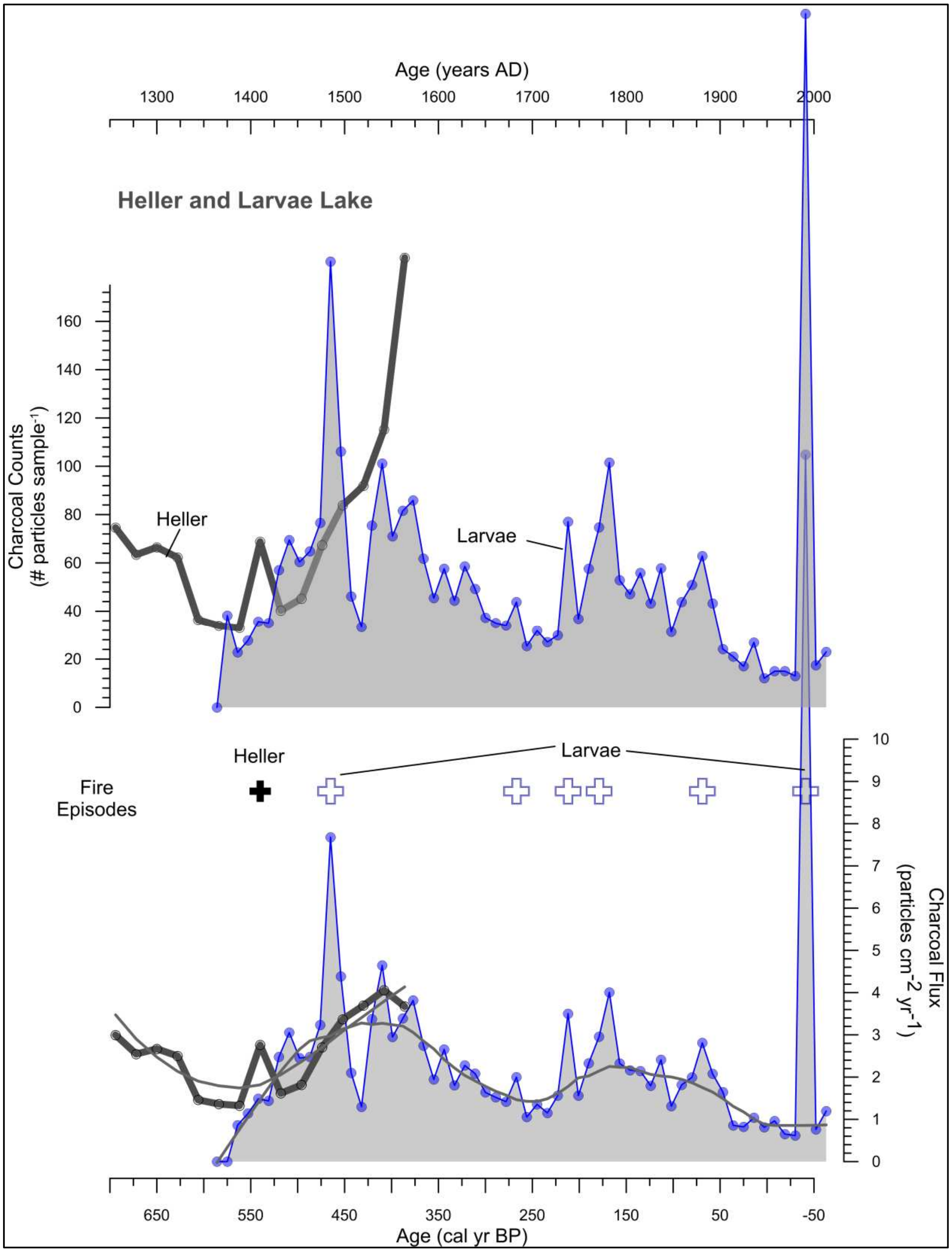

Figure 9. Comparison of Larvae Lake and HLDGM sedimentary charcoal records showing raw charcoal counts, fire episodes, and charcoal flux.

with tree-ring inferred drought conditions in Ashley Creek (Carson & Munroe 2005). The closest fire episode from HLDGM to the Larvae Lake records occurs approximately 465 cal yr BP (1485 AD), vs. 540 cal yr BP, respectively. The 70-year difference is within one standard deviation of the radiocarbon chronologies and could likely be the same fire episode. Larvae Lake charcoal flux (ranging between 0 to 16.74 particles $cm^{-2}yr^{-1}$) shows some variation between peaks, but generally charcoal is low between fire episodes, with a FRI of 79-129 yrs (fire frequency ranged between 2 and 6 events/500 years). Larvae Lake fire episodes and fire-scarred tree ring sites from Heyerdahl et al. (2011) show 3 fire events that correspond to Larvae Lake episodes at 1881 AD, 1870 AD, and 1845 AD for both tree and sedimentary charcoal. The two Heyerdahl et al. (2011) sites, BRO and MUR, are located 28 km apart from each other and are 23 and 7.3 km from Larvae, respectively, and 39 and 11 km from HLDGM, respectively (Figure 1). The signal is picked up in both the charcoal and the dendrochronology records, suggesting the middle and late 19th century experienced several large regional scale fires burning across multiple vegetation zones. The 1683 AD fire episode identified at Larvae Lake could also be a match to the fire scars occurring at either 1650 AD or 1680 AD recorded at the BRO site. All together, the fire frequency of HLDGM ranged between 3 and 7 events/1000 years, with the most frequent episodes occurring during the early-to-mid-Holocene transition. The average smoothed fire return interval for the entire record is 220 $yr^{-1}fire^{-1}$, and averages for zone 1 (176 $yr^{-1}fire^{-1}$), zones 2-4 (212 $yr^{-1}fire^{-1}$), and zone 5 (276 $yr^{-1}fire^{-1}$), suggesting that although the fire frequency lengthens some through each zone, frequency stays relatively the same throughout the Holocene.

The Larvae Lake record shows a 600-year fire history with an approximate 200-

year fire return interval. Looking at this record allows us to ask if the Neola fire was an unprecedented event. The 2007 Neola fire was large and destructive, and looking at the event solely from the perspective of the Larvae Lake fire history makes it appear to be a large, unprecedented fire. The 13,000-yr record from HLDGM provides the context for exploring the uniqueness of the Neola fire. The peak magnitude of the Neola fire at Larvae Lake was 170 $cm^{-2}peak^{-2}$ (Figure 7); comparing that peak magnitude to the entire HLDGM record suggests that there were at least 14 fires as large as or larger than the 2007 Neola fire. With increasingly warmer climates and increasing fire activity (Westerling et al. 2006, Marlon et al. 2012, Joyce et al. 2013b, Dennison et al. 2014), we can expect more large fires in the future. If the early-to-mid-Holocene transition were an analogue for future fire conditions, with longer and warmer summers, then we should expect more fires and potential rearrangement of vegetation communities. Increasing fire in high elevation systems has led to a major vegetation change in the past and should become a management priority for the future.

CHAPTER 5

CONCLUSION

The location of HLDGM is near the boundary of an ecotone and the record highlights a large-scale ecotone shift from open spruce parkland to closed-canopy pine forest in the mid-Holocene. This suggests the sub-alpine treeline moving upwards in elevation in response to warming climates, supporting the first hypothesis. The draining of the lake and the impact of other disturbance factors make it difficult to ascertain the vegetation response to the MCA or the LIA. However, the persistence of the closed-canopy pine forest that was established during the mid-Holocene suggests that even if the vegetation did respond during these two multicentennial climate events, the overall vegetation composition remained intact, suggesting potential resiliency within the historic vegetation communities. Although there has been some lengthening of the FRI through the five zones, with a 100-year difference between zone 1 and zone 5 (176 vs. 276 $yr^{-1}fire^{-1}$), they are all still close to the average of the entire record which is 220 $yr^{-1}fire^{-1}$, suggesting that the FRI has been relatively stable through the Holocene; this supports the second hypotheses, that fire frequency in montane ecosystems has remained consistent through time, with fire events occurring on average every few centuries. Finally, our analyses suggests the third hypothesis, that 20th-century management activities have impacted vegetation communities and fire regimes in the mid-elevation Uinta Mountains, is scale dependent. Although there does not appear to be a direct impact of fire suppression activities at HLDGM, the Larvae Lake record does suggest the Neola North fire is anomalous in the last ~500 years. Suppression activities may have contributed to the build-up of fuels during the 20th century amplifying the size and intensity of the Neola North fire, allowing it to spread from low-to-high elevation.

REFERENCES

Alley, R.B., 2000. The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews* 19(1), 213–226.

Alley, R.B., & Agustsdottir, A.M., 2005. The 8k event: cause and consequences of a major Holocene abrupt climate change. *Quaternary Science Reviews* 24, 1123-1149.

Anderson, M.D., 2003. *Pinus* contorta var. latifolia. In: *Fire Effects Information System [Online]*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis/plants/tree/pinconl/all accessed 11/27/2013.

Associated Press, 2007, July 9. Interstates closed again for record setting Utah wildfire. *The San Diego Union-Tribune.* Retrieved from http://legacy.utsandiego.com/news/nation/20070709-0726-wst-utahwildfires.html

Berger, A., & Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews*, 10, 297-317.

Briggs, G.M., & MacMahon, J.A., 1983. Alpine and subalpine wetland communities of the Uinta Mountains, Utah. *The Great Basin Naturalist*, 43(4), 523-530.

Bryant, B., 1992. Geologic and structure maps of the Salt Lake City 1° x 2° quadrangle, Utah and Wyoming: *U.S. Geological Survey Miscellaneous Publication Series*, map I-1997, scale 1:125,000.

Carrara, P.E., Short, S.K., & Shroba, R.R., 1985. A pollen study of Holocene peat and lake sediments, Leidy Peak area, Uinta Mountains, Utah. *Geology Studies*, 32(1), 1-7.

Carson, E.C., 2003. Fluvial responses to Holocene environmental change, Uinta Mountains, northeastern Utah: Ph.D. dissertation, University of Wisconsin-Madison, Madison, WI, 525 p.

Carson, E.C., & Munroe, J.S., 2005. Tree-ring based streamflow reconstruction for Ashley Creek, northeastern Utah: implications for palaeohydrology of the southern Uinta Mountains. *The Holocene*, 15(4), 602-611.

Clark, P.U., Shakun, J.D., Baker, P.A., Bartlein, P.J., Brewer, S., Brook, E., Carlson, A.E., Cheng, H., Kaufman, D.S., Liu, Z., Marchitto, T.M., Mix, A.C., Morrill, C., Otto-Bliesner, B.L., Pahnke, K., Russell, J.M., Whitlock, C., Adkins, J.F., Blois, J.L., Clark, J., Colman, S.M., Curry, W.B., Flower, B.P., He, F., Johnson, T.C., Lynch-Stieglitz, J., Markgraf, V., McManus, J., Mitrovica, J.X., Moreno, P.L., & Williams, J.W., 2012. Global climate evolution during the last deglaciation. *Proceedings of the National Academy of Science,* 109(19), E1134-E1142.

Chamberlin, T.C., 1890. The method of multiple working hypotheses. *Science*, 15(92).

COHMAP, 1988. Climatic changes of the last 18,000 years: observations and model simulations. *Science* 241, 1043-1052.

Dean, W.E., 1974. Determination of carbonate and organic matter in calcareous sediments by loss on ignition comparison to other methods. *Journal of Sedimentary Petrology*, 44, 242-248.

Dehler, C.M., & Sprinkel D.A., 2005. Revised stratigraphy and correlation of the Neoproterozioic Uinta Mountain Group, Northeastern Utah. In Dehler, C. M., Pederson, J. L., Sprinkel, D. A., & Kowallis, B.J. (eds.), *Uinta Mountain Geology*. Utah Geologic Association Publication 33, 17-30.

Dennison, P.E., Brewer, S.C., Arnold, J.D., & Moritz, M.A., 2014. Large wildfire trends in the western United States, 1984-2011. *Geophysical Research Letters*, DOI: 10.1002/2014GL059576

Ellison, C.R.W., Chapman, M.R., & Halt, I.R., 2006. Surface and deep ocean interactions during the cold climate event 8200 years ago. *Science*, 312, 1929-1932.

Faegri, K., Kaland, P.E., & Krzywinski, K., 1989. *Textbook of Pollen Analysis 4th ed*. Caldwell, NJ: The Blackburn Press.

Fall, P.L., 1992. Spatial patterns of atmospheric pollen dispersal in the Colorado Rocky Mountains, USA. *Review of Palaeobotany and Palynology*, 74, 293-313.

Finkelstein, S.A., 2010. The changing biosphere: recent insights from paleoenvironmental science into drivers, mechanisms and impacts. *The Canadian Geographer/Le Gèographe Canadien*, 54(2), 133-138.

Froyd, C.A., & Willis, K.J., 2008. Emerging issues in biodiversity and conservation management: the need for a paleoecological perspective. *Quaternary Science Reviews*, 27, 1723-1732.

Graham, N.E., Hughes, M.K., Ammann, C.M., Cobb, K.M., Hoerling, M.P., Kennett, D.J., Kennett, J.P., Rein, B., Stott, L., Wigand, P.E., & Xu, T., 2007. Tropical Pacific – mid-latitude teleconnections in medieval times. *Climatic Change*, 83, 241-285.

Grimm, E., 1987. CONISS: A FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geosciences,* 13(1), 13–35.

Hayward, L., 1952. Alpine biotic communities of the Uinta Mountains, Utah. *Ecological Monographs*, 22(2), 93-120.

Heiri, O., Lotter, A.F., & Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25, 101-110.

Heyerdahl, E.K., Brown, P.M., Kitchen, S.G., & Weber, M.H., 2011. Multi-century fire and forest histories at 19 sites in Utah and Eastern Nevada.Gen.Tech.Rep. RMRS-GTR-261WWW. Fort Collins, CO: *U.S. Department of Agriculture, Forest Service, Rocky Mountains Research Station*. 192p.

Higuera, P.E., Gavin, D.G., Bartlein, P.J., & Hallett, D.J., 2010. Peak detection in sediment-charcoal records: impacts of alternative data analysis methods on fire-history interpretations. *International Journal of Wildland Fire* 19, 996-1014.

Joyce, L.A., Running, S.W., Breshears, D.D., Dale, V.H., Malmsheimer, R.W., Sampson, R.N., Sohngen, B., & Woodall, C.W., 2013a. Forestry in *National Climate Assessment Development Report* http://ncadac.globalchange.gov/ accessed 12/9/2013

Joyce, L.A., Briske, D.D., Brown, J.R., Polley, H.W., McCarl, B.A., & Bailey, D.W., 2013b. Climate change and North American rangelands: Assessment of mitigation and adaptation strategies. *Rangeland Ecology & Management*, 66(5), 512-528.

Kapp, R.O., Davis, O.K., & King, J.E., 2000. *Pollen and Spores*. American Association of Stratigraphic Palynologists, New York.

Koll, R., 2011. Long-term vegetation, climate and fire history in the eastern Uinta Mountains, Utah, U.S.A. Unpublished Master's Thesis. University of Utah.

Laabs, B.J.C., & Carson, E.C., 2005. Glacial geology of the southern Uinta Mountains. In Dehler, C. M., Pederson, J. L., Sprinkel, D. A., & Kowallis, B.J. (eds.), *Uinta Mountain Geology*. Utah Geologic Association Publication 33, 235-253.

Lotan, J., Brown, J., & Neunschwander, L., 1985. Role of fire in Lodgepole Pine forests. In Baumgartner, D. et al. (eds.) *Lodgepole pine the species and its management Symposium Proceedings*. Washington State University, Pullman, 133-152.

MacDonald, G.M., & Tingstad, A.H., 2007. Recent and multicentennial precipitation variability and drought occurrence in the Uinta Mountain region, Utah. *Arctic, Antarctic, and Alpine Research*, 39(4), 549-555.

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., & Ni, F., 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 326, 1256-1260.

Marlon, J.R., Bartlein, P.J., Gavin, D.G., Long, C.J., Anderson, R.S., Briles, C.E., Brown, K.J., Colombarol, D., Hallett, D.J., Power, M.J., Scharf, E.A., & Walsh, M.K., 2012. Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Science*, DOI: 10.1073/pnas.1112839109

Martin, K., 2007. Neola North Fire Update. Rocky Mountain Incident Management Team. http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsm9_002372.pdf accessed 12/1/2013.

Martinson, D.G., Pisas, N.G., Hays, J.D., Imbre, J., Moore, T.C., & Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. *Quaternary Research* 27, 1-29.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., & Steig, E.J., 2004. Holocene climate variability. *Quaternary Research*, 62, 243-255.

Mauk, R., & Henderson, J., 1984. Coniferous forest habitat types of northern Utah. *USDA Forest Service Intermountain Forest and Rangeland Experimental Station*. General Technical Report INT-170. 89pp.

Minckley, T.A., Bartlein, P.J., Whitlock, C., Shuman, B.N., Williams, J.W., & Davis, O.K., 2008. Associations among modern pollen, vegetation, and climate in western North America. *Quaternary Science Reviews*, 27, 1962-1991.

Munroe, J.S., 2003. Holocene timberline and paleoclimate of the northern Uinta Mountains, northeastern Utah, USA. *The Holocene*, 13(2), 175-185.

Munroe, J.S., & Laabs, B.J.C., 2009. Glacial geologic map of the Uinta Mountains area, Utah and Wyoming: *Utah Geological Survey Miscellaneous Publication* 09-4DM, GIS data, 1 plate, scale 1:100,000.

Munroe, J.S., Laabs, B.J.C., Shakun, J.D., Singer, B.S., Mickelson, D.M., Refsnider, K.A., & Caffee, M.W., 2006. Latest Pleistocene advance of alpine glaciers in the southwestern Uinta Mountains, Utah, USA: evidence for the influence of local moisture sources. *Geology*, 34, 841-844.

National Interagency Fire Center (NIFC). http://www.nifc.gov. Accessed 12/9/2013.

National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center. http://www.ncdc.noaa.gov/temp-and-precip. Accessed 12/9/2013

National Research Council, 2011. Impacts in the next few decades and coming centuries. In *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia*. Washington, DC: The National Academies Press.

Pielou, E.C., 1991. *After the Ice Age: the return of life to glaciated North America.* Chicago, Illinois: The University of Chicago Press.

PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 2 Feb 2011.

Pyne, S.J., Andrews, P.L., & Laven R.D., 1996. *Introduction to Wildland Fire 2nded.* New York, NY: John Wiley & Sons, Inc.

Refsnider, K.A., Laabs, B.J.C., Plummer, M.A., Mickelson, D.M., Singer, B.S., & Caffee, M.W., 2008. Last glacial maximum climate inferences from cosmogenic dating and glacier modeling of the western Uinta ice field, Uinta Mountains, Utah. *Quaternary Research*, 69, 130-144.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk-Ramsay, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hattie, C., Heaton, T.J., Hogg, A.G., Hugen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., & van der Plicht, J., 2013. IntCal13 and MARINE13 radiocarbon are calibration curves 0 – 50000 years cal BP. *Radiocarbon* 55(4). DOI: 10.2458/azu_js_rc.55.16947.

Richardson, D.M., 1998. *Ecology and biogeography of Pinus.* New York, NY: Cambridge University Press.

Seppä, H., & Bennett, K.D., 2003. Quaternary pollen analysis: recent progress in palaeoecology and palaeoclimatology. *Progress in Physical Geography*, 27(4), 548-579.

Shaw, J.D., & Long, J.N., 2007. Forest ecology and biogeography of the Uinta Mountains, U.S.A. *Arctic, Antarctic, and Alpine Research*, 39(4), 614-628.

Schoennagel, T., Veblen, T.T., & Romme, W.H., 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. *Bioscience*, 54(7), 661-676.

Stuiver, M., & Reimer, P.J., 1993. Extended 14C data base and revised CALIB 3.0 14C Age calibration program. *Radiocarbon*, 35, 215-230

Tingstad, A.H., Moser, K.A., MacDonald, G.M., & Munroe, J.S., 2011. A ~13,000-year paleolimnological record from the Uinta Mountains, Utah, inferred from diatoms and loss-on-ignition analysis. *Quaternary International*, 235, 48-56.

Thompson, R., Battarbee, R.W., O'Sullivan, P.E., & Oldfield, F., 1975. Magnetic Susceptibility of lake sediments. *Limnology and Oceanography* 20(5), 687-698.

Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., & Frank, D.C., 2009. Persistent positive north Atlantic oscillation mode dominated the Medieval Climate Anomaly. *Science*, 324, 78-80.

Welsh, S.L., Atwood, N.D., Goodrich, S., & Higgins, L.C., 2008. *A Utah Flora 4th Edition, revised*. Provo, Utah: Brigham Young University.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., & Swetnam, T.W., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, 303, 940-943.

Whitlock, C., & Larsen, C., 2001. Charcoal as a fire proxy. In J.P. Smol, H.J.B. Birks & W.M. Last (eds.), 2001. *Tracking Environmental Change Using Lake Sediments. Vol 3: Terrestrial, Algal, and Silaceous Indicators*. Dordrecht, The Netherlands: Kluwer Academic Press.

Williams, J.W., Shuman, B.N., Webb, T., Bartlein, P.J., & Leduc, P.L., 2004. Late quaternary vegetation dynamics in North America: scaling from taxa to biomes. *Ecological Monographs* 72(2), 309-334.

Willis, K.J., Bailey, R.M., Bhagwat, S.S., & Birks, H.J.B., 2010. Biodiversity baselines, thresholds and resilience: testing prediction and assumptions using palaeoecological data. *Trends in Ecology and Evolution*, 25, 583-591.

Uchytil, R.J., 1991. *Picea* engelmanii. In: *Fire Effects Information System [Online]*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis accessed 11/27/2013.

U.S. Geological Survey, 1999. Digital representation of "Atlas of United States Trees" by Elbert L. Little, Jr.. http://gec.cr.usgs.gov/data/little/ accessed 6/4/2014

Varney, R.A., Cummings, L.S., Winsborough, B., & Puseman, K., 2004. Feasibility study of pollen, diatom, and macrofloral analyses at Heller Lake, Utah, with supporting archeoclimate models. *Paleo Research Institute Technical Report 04-19.*

Viau, A.E., Gajewski, K., Sawada, M.C., & Fines, P., 2006. Millennial-scale temperature variations in North America during the Holocene. *Journal of Geophysical Research*, 111, D09102.